Tellus (1985), *37B*, 53–63

Solar absorption by atmospheric water vapor: a comparison of radiation models

By DAVID P. KRATZ and ROBERT D. CESS
Laboratory for Planetary Atmospheres Research, State University of New York, Stony Brook, New York 11794, U.S.A.

(Manuscript received July 4; in final form October 30, 1984)

ABSTRACT

We have intercompared several different procedures for evaluating solar absorption by atmospheric water vapor, and in particular we have employed a random band model as a diagnostic tool for assessing approximations which are inherent in existing parameterizations. We reaffirm McDonald's (1960) conclusion as to the importance of the 0.72 and 0.81 μm water vapor absorption bands, and we find that the Goody random band model and the Lacis–Hansen empirical parameterization produce comparable tropospheric heating rates. This agreement does not extend to the stratosphere, for which water vapor amounts lie outside the intended range of applicability of the Lacis–Hansen parameterization. But when diurnal averaging is taken into account, the disagreement is reduced. We further present what is in effect a two-parameter extension of the Lacis–Hansen parameterization.

1. Introduction

Recent studies (e.g., Wang, 1976; Chou and Arking, 1981; Fouquart and Bonnel, 1980; and Slingo and Schrecker, 1982) indicate that there are apparent discrepancies concerning parameterizations of the absorption of solar radiation by atmospheric water vapor. For example, employing two-parameter Curtis–Godson scaling in conjunction with the Goody random band model, Wang (1976) obtains atmospheric heating rates which, throughout the troposphere, are considerably smaller (by as much as 0.5 K day^{-1}) than those determined from the Lacis and Hansen (1974) parameterization of Yamamoto's (1962) absorption curve. Similar differences, but with restriction to the lower troposphere, and with maximum discrepancies of roughly 0.2 K day^{-1}, have been reported by Chou and Arking (1981), and by Slingo and Schrecker (1982). Moreover, both of these studies indicate that the Lacis and Hansen parameterization underestimates heating rates within the upper troposphere and stratosphere by as much as 0.2 to 0.3 K day^{-1}.

The purpose of the present paper is to attempt to understand the above discussed discrepancies concerning solar absorption by atmospheric water vapor. To this end we employ several two-parameter random band models, utilizing the most recent compilation of molecular line parameters for water vapor (Rothman, 1981). These models are then employed in the role of interpretive models as a means of assessing approximations which are inherent in existing parameterizations. In addition, we present what is in effect a two-parameter extension of the one-parameter Lacis and Hansen formulation.

2. Random band models

In this section we briefly review three random band models, those due to Goody (1952), Malkmus (1967) and Wallace et al. (1974), all of which incorporate the assumption of Lorentzian lines. Letting $T_{\Delta\omega}$ denote the transmissivity for a given narrow spectral interval $\Delta\omega$, where ω is wavenumber, the Goody random band model may be expressed as

$$T_{\Delta\omega} = \exp\{-(\sigma w/\delta)[1 + (\sigma w/\pi\alpha)]^{-1/2}\}, \quad (1)$$

where σ is the mean line strength for the spectral interval $\Delta\omega$, α and δ are, respectively, the corresponding mean line half-width and mean line spacing, and w is the absorber amount. This model assumes the line intensity distribution $P(S) = (1/\sigma)\exp(-S/\sigma)$, where $P(S)$ is the probability that a given rotational line has the intensity S.

The Malkmus model, on the other hand, utilizes the line intensity distribution $P(S) = (N/S)\,\bar{S}\exp(-S/\bar{S})$, where N and $\bar{S}$ are normalization constants, with the result that

$$T_{\Delta\omega} = \exp\{(\pi\alpha/2\delta)[\sqrt{1 + (4\sigma w/\pi\alpha)} - 1]\}. \quad (2)$$

A further random band model is that due to Wallace et al. (1974), and essentially this is an analytic approximation to a second random band model proposed by Goody (1964), for which $P(S) = K/S$ for $S \leqslant S'$, where K and S' are again normalization constants. This model yields

$$T_{\Delta\omega} = \exp\{-2\pi y F(u)\}, \quad (3)$$

where

$$F(u) = u/(1 + 0.515u^{1/2}; \quad u < 4$$
$$= (0.5 + 4u - 0.03125/u) \times (2\pi u)^{-1/2} - 1; \quad u > 4,$$

while $u = 16w/2\pi\sigma\alpha$ and $y = \pi\alpha/16\delta$.

It is important to emphasize that eqs. (1), (2) and (3) are mutually consistent in the weak-line and strong-line limits (e.g., see Rodgers, 1968, for a discussion of the Malkmus model). As illustrated by Goody, in the weak-line limit

$$T_{\Delta\omega} = 1 - \sigma w/\delta, \quad (4)$$

whereas in the limit of strong rotational lines

$$T_{\Delta\omega} = \exp(-\sqrt{\pi\sigma\alpha w}/\delta). \quad (5)$$

Thus eqs. (1), (2) and (3) essentially provide alternate means of interpolating between eqs. (4) and (5).

3. Absorptance results

To facilitate an initial intercomparison of band models and parameterized absorptance formulations, attention is first directed to comparing the fractional solar absorptance in a homogeneous atmosphere. Specifically, this pertains to a comparison of the three random bandmodels, the Lacis and Hansen (1974) parameterization, and the solar absorptance results of Chou and Arking (1981). Moreover, the Goody random band model will be employed to illustrate the relative importance of the 0.72, 0.81 and 6.3 μm water vapor bands.

As demonstrated by McDonald (1960), due to the large amount of solar energy contained within the spectral region of the weak 0.72 and 0.81 μm bands, these bands cannot be neglected when calculating the absorption of solar radiation by water vapor. Consequently Yamamoto (1962) augmented the absorptance measurements of Howard et al. (1956), who did not measure these bands, with estimates from Fowle's (1915) absorptance measurements of the 0.72 and 0.81 μm bands. These absorptance measurements were then weighted by the solar flux and summed to produce a total absorptive curve as a function of water vapor amount (Yamamoto, 1962). A simple fit to this absorption curve was given by Lacis and Hansen (1974) as

$$A = \frac{2.9w}{(1 + 141.5w)^{0.635} + 5.925w}, \quad (6)$$

where A denotes the fractional absorptance of solar radiation by water vapor at standard temperature and pressure ($T_0 = 273$ K and $P_0 = 1013$ mb). Lacis and Hansen (1974) state that eq. (5) fits Yamamoto's absorption curve with an error $\leqslant$1% for $10^{-2} \leqslant w \leqslant 10$ g cm^{-2}.

For conditions other than standard temperature and pressure, Lacis and Hansen employ an effective water vapor amount

$$w_{\text{eff}} = w(P/P_0)(T_0/T)^{1/2}, \quad (7)$$

and it is important to emphasize that the condition $w_{\text{eff}} \geqslant 10^{-2}$ g cm^{-2} is violated for stratospheric applications. Thus it might be expected that, as discussed in the Introduction, the use of eq. (6) could produce inappropriate stratospheric heating rates.

With regard to the random band models discussed in the previous section, the spectroscopic data used in the present investigation were derived from the 1980 version of the Air Force Geophysics Laboratory atmospheric absorption line parameters compilation (Rothman, 1981), which is the latest available version of the work by

Table 1. *The spectral intervals of the solar and near infrared bands of water vapor given in* cm^{-1}

Band (μm)	Present	Yamamoto	Chou & Arking
0.72	13,270–14,500	13,514–14,286	—
0.81	11,500–12,940	11,905–12,658	11,600–12,040
0.94	9,700–11,500	9,700–11,500	9,600–11,600
1.14	8,200–9,700	8,200–9,700	8,200–9,600
1.38	6,200–8,200	6,200–8,200	6,300–8,200
1.87	4,400–6,200	4,800–6,200	4,400–6,300
2.7/3.4	2,500–4,400	2,800–4,400	2,600–4,400
6.3	1,000–2,200	1,015–2.160	—

McClatchey et al. (1973). The spectral parameters employed within the random band models utilize the bands listed in Table 1, and these encompass all of the bands considered by Yamamoto (1962), from which eq. (6) was derived. Moreover, the computations were carried out with $\Delta\omega = 5$ cm^{-1}. As discussed by Kiehl and Ramanathan (1982) with respect to atmospheric CO_2, there is little difference whether an interval of 5 cm^{-1} or smaller is employed, and we have confirmed this for the present application. However, as also indicated by Kiehl and Ramanathan, and as we have further confirmed, significant errors can occur if the interval size is greater than about 10 cm^{-1}. For example, increasing the inverval size from 5 to 25 cm^{-1} produces, within the Goody model, a roughly 13% increase in fractional absorptance. As a final point, we employed the results of Thekaekara (1972) for the spectral solar flux.

In Fig. 1 we compare, for standard temperature and pressure, the three random band models with the Lacis and Hansen (1974) parameterization of Yamamoto's (1962) absorption curve. There is little difference between the three band models, while the differences between the Goody model and the Lacis and Hansen parameterization is less than 5%.

Chou and Arking (1981) also present solar absorption results for a homogeneous atmosphere, in this case for a temperature of 240 K and a

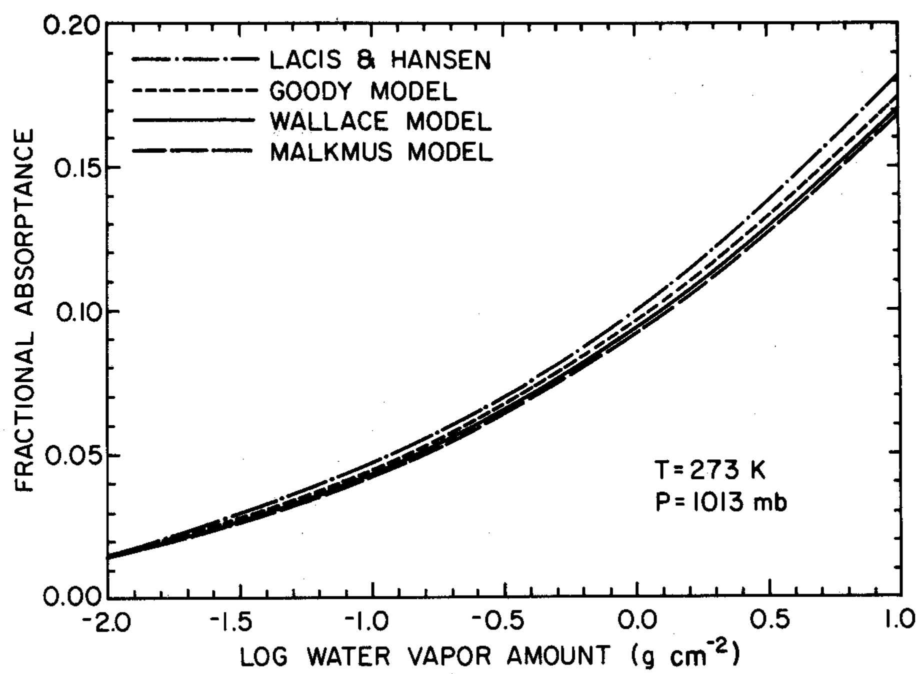

Fig. 1. A comparison of fractional absorptance as determined from the three random band models and the Lacis and Hansen parameterization for $P = 1013$ mb and $T = 273$K.

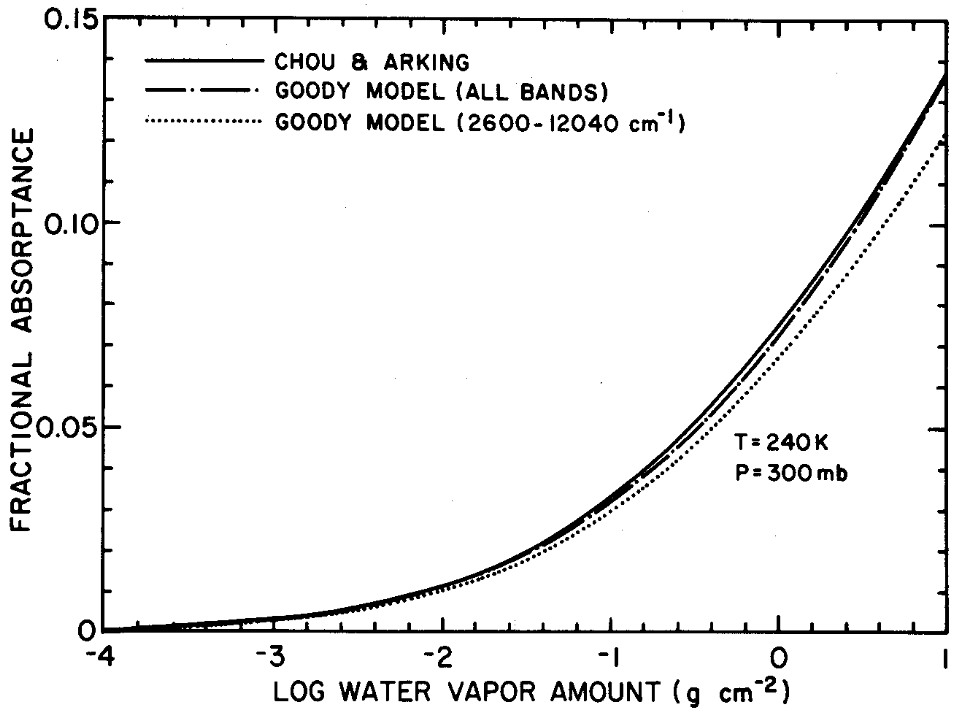

Fig. 2. A comparison of fractional absorptance as determined by Chou and Arking and from the Goody random band model for $P = 300$ mb and $T = 240$K.

pressure of 300 mb (their Table 3), which are based upon a 30 term exponential sum fit to a line-by-line calculation. Our use of the Goody model yields results which are in excellent agreement with their values, as can be seen from Fig. 2. But this close agreement is partially fortuitous, since our use of the Goody model incorporates more absorption bands than does their calculation. As summarized in Table 1, Chou and Arking neglect the 6.3 and 0.72 μm bands, as well as most of the 0.81 μm band. When we degrade our spectral range to theirs (2600–12,040 cm^{-1}), the Goody model yields a fractional absorptance which is about 10% less than Chou and Arking.

At this point a cautionary comment must be injected. In performing their line-by-line calculations, Chou and Arking employed a spectral interval of 0.02 cm^{-1}, which might be somewhat large, since for the conditions of Fig. 2 (300 mb and 240 K) the Lorentz half-width for water vapor is roughly 0.025 cm^{-1}. In an earlier line-by-line calculation for water vapor (Ludwig et al., 1973), a spectral interval of 0.001 cm^{-1} was chosen.

Returning to Fig. 1, the agreement between the Goody model and the Lacis and Hansen empirical parameterization suggest that it would be useful to employ band models as a device for obtaining a solar absorption parameterization which has a greater range of applicability than the Lacis–Hansen parameterization. To this end we assume, as in the random band models, a two-parameter formulation (broadening pressure and absorber amount). Such a parameterization for both the Goody and Malkmus models, applicable for $T_0 =$ 273 K, is of the form

$$A = \frac{w}{a + bw^c + dw}, \tag{8}$$

where a, b, c and d are pressure-dependent coefficients as given in Table 2. For temperatures other than 273 K, P is replaced by the effective pressure

$$P_{eff} = (273/T)^{0.62}, \tag{9}$$

where this corrects for the temperature dependence of the line half-widths. moreover, the effective absorber amount is

$$w_{eff} = w(T/273)^{\varepsilon}, \tag{10}$$

where

$$\varepsilon = 0.60 - 0.20|\text{Log}_{10} P_{eff} + 0.5|,$$

and this corrects for the temperature dependence of the line intensities.

Table 2. *Parameterization coefficients for eq. (8), with P denoting total pressure in atmospheres*

Goody model
$a = 0.1018 + 0.0063(-\log_{10} P)^{2.424}$
$b = 3.4488 + 2.8452P^{-0.5} + P^2$
$c = 0.4968 + 0.0900P^{0.5}$
$d = 3.0593 + 2.0593(-\log_{10} P)$
Malkmus model
$a = 0.1084 + 0.0160(-\log_{10} P)^{1.681}$
$b = 3.8083 + 2.836P^{-0.5} + P^2$
$c = 0.49072 + 0.08679P^{0.5}$
$d = 3.2094 + 2.1094(-\log_{10} P)$

Note from eq. (8) and Table 2 that in the limit of small P and large w/P, both parameterizations essentially reduce to

$$A \simeq 0.35\sqrt{Pw}, \qquad (11)$$

which represents the proper functional form for small P and large w/P (i.e., the limit of strong nonoverlapping rotational lines), while for small w the proper linear limit is achieved. Eq. (8) is applicable for $10^{-4} \leqslant w \leqslant 10$ gm/cm^2 and $10^{-3} \leqslant P \leqslant 1$ atm, appropriate throughout the troposphere and most of the stratosphere. For these ranges eq. (8) produces a standard deviation of 1.2% relative to the respective Goody and Malkmus random band models.

As discussed in the following section, in order to accurately parameterize both stratospheric and tropospheric heating rates, it is necessary to employ a two-parameter formulation as in eq. (8), and it is for this reason that we have not attempted to re-fit the single-parameter Lacis–Hansen parameterization. However, even with this added degree of complexity, eq. (8) provides a substantial reduction in computational effort, relative to a random band model, since for 5 cm^{-1} intervals a random band model requires 2674 intervals.

4. Heating rate results

In order to further illustrate the similarities or differences between various solar absorption models, atmospheric heating rates have been evaluated from the expression

$$\frac{\Delta T}{\Delta t} = \frac{\mu g}{c_p} \frac{\Delta F}{\Delta P}, \qquad (12)$$

where μ = cos (solar zenith angle), g is gravitational acceleration, c_p is the specific heat at constant pressure, and ΔF is the change in net solar flux over the pressure interval ΔP. For comparative purposes we employ the McClatchey et al. (1972) midlatitude summer atmosphere, a surface albedo of zero, and initially $\mu = 0.5$. The evaluation of eq. (12) utilizes 1 km vertical intervals together with the Curtis–Godson approximation as described by Rodgers and Walshaw (1966).

A comparison of heating rates as evaluated employing eq. (8) for both the Goody and Malkmus models, and the Lacis–Hansen eq. (6), are illustrated in Fig. 3. The agreement is quite reasonable throughout the troposphere, whereas relative to the random band model parameterizations, the Lacis–Hansen parameterization appears to significantly underestimate stratospheric heating rates. As discussed in Section 3, the Lacis–Hansen parameterization is actually not applicable for stratospheric water vapor amounts, and thus it is not surprising that this parameterization underestimates stratospheric heating rates. But at least part of the difference shown in Fig. 3 is a manifestation of the McClatchey et al. (1972) model atmosphere, for which the water vapor mass mixing ratio decreases with altitude to a value of 3.6×10^{-6} at 15 km, above which it increases, attaining a value of 1.6×10^{-5} at 25 km. There is no observational justification for an increasing mass mixing ratio above 15 km (e.g., Harries, 1976).

As an alternative, we have replaced the McClatchey et al. mass mixing ratio for altitudes greater than 15 km by their 15 km value of 3.6×10^{-6}. The corresponding heating rates are illustrated in Fig. 4, in addition to heating rates due to Chou and Arking (1981) and Wang (1976) which will shortly be discussed, and it is seen that this significantly diminishes the difference, within the stratosphere, between the Lacis–Hansen parameterization and the two random band models.

But there is yet another facet involved. The results shown in Figs. 3 and 4 refer to *instantaneous* heating rates, whereas stratospheric time constants are much longer than a day. Thus with respect to radiative perturbations, diurnal averages are more meaningful than instantaneous quantities. A comparison of diurnally-averaged heating rates is shown in Fig. 5 for a latitude and solar declination angle, respectively, of $\phi = 35°$N and δ

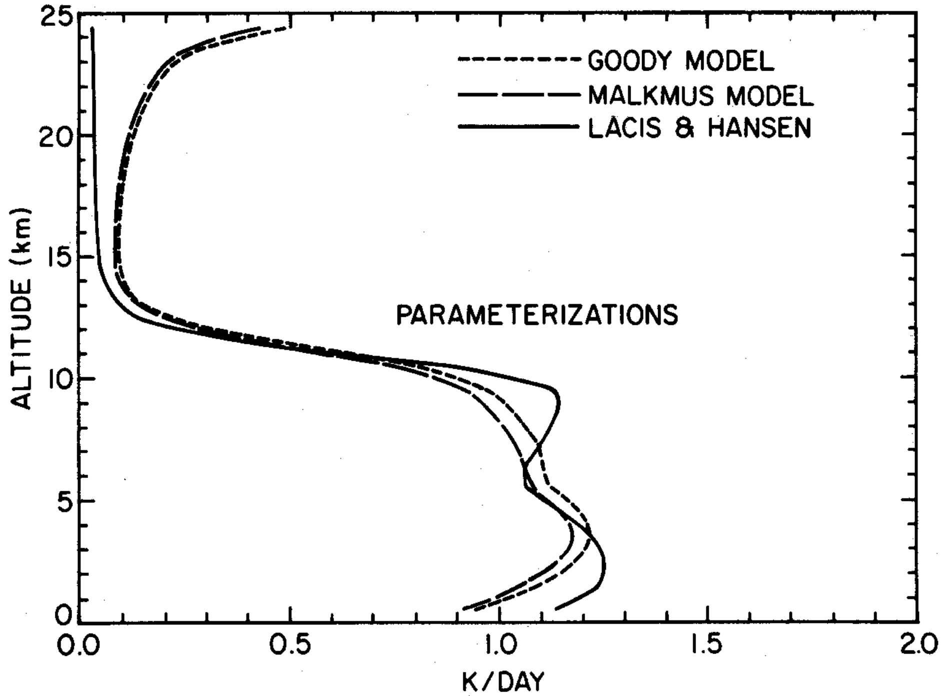

Fig. 3. A comparison of atmospheric heating rates employing the McClatchey et al. midlatitude summer atmosphere.

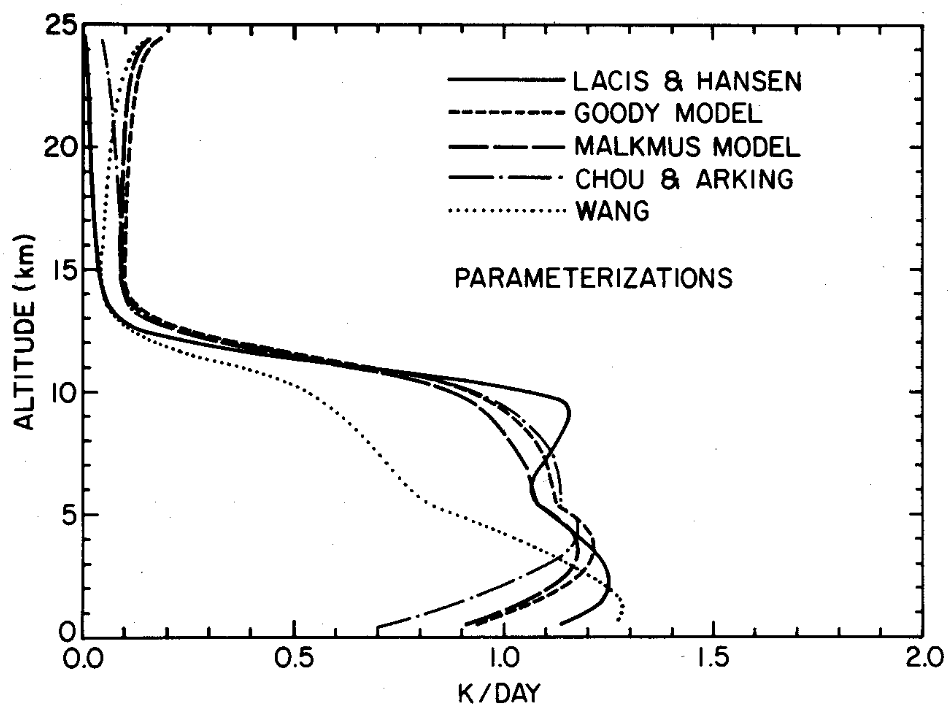

Fig. 4. A comparison of atmospheric heating rates employing the McClatchey et al. midlatitude summer atmosphere, but with a water vapor mass mixing ratio of 3.6×10^{-6} for $Z \geqslant 15$ km.

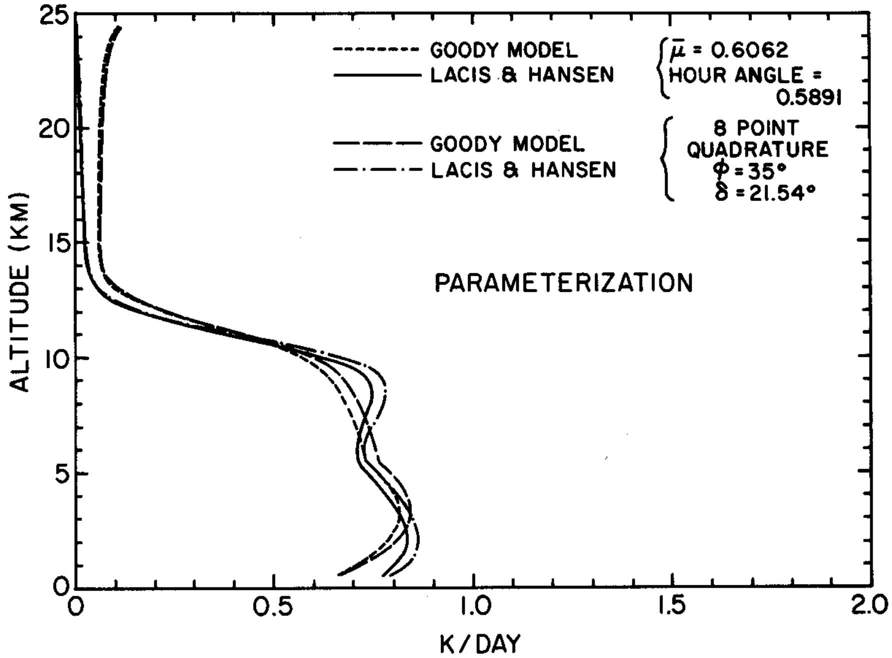

Fig. 5. A comparison of atmospheric heating rates for the same water vapor mass mixing ratio as in Fig. 4, and for average-sun results versus diurnal averaging.

= 21.54°, the latter value corresponding to 15 July. This averaging was performed using an 8-point Gaussian quadrature. From Fig. 5 it is clear that, when diurnal averaging is taken into account, there is even less of a difference between the parameterization of the Goody model and the Lacis–Hansen parameterization. Also illustrated in Fig. 5 are results employing average input parameters, applicable for $\phi = 35°$N and 15 July, of $\bar{\mu} = 0.6062$ and hour angle (i.e., daytime fraction) = 0.5891, from which it is seen that there is little difference between performing a diurnal average or using an average sun position with day-night averaging.

Of course, there remains a significant *relative* error in stratospheric heating rates determined from the Lacis–Hansen parameterization in progressing from Fig. 3 to Fig. 5. But the point here is that the *absolute* heating rates have been substantially reduced. Thus, relative to other stratospheric heating/cooling rates (e.g., due to CO_2 and O_3), the absolute error produced by the Lacis–Hansen parameterization in determining the *net* stratospheric heating rate is reduced in Fig. 5 relative to Fig. 3. Moreover, infrared stratospheric heating/cooling rates will not be influenced by diurnal averaging.

Returning to Fig. 4, the Chou and Arking (1981) curve was determined from their Table 3 together with their wing-scaling approximation. As they discuss, their heating rates within the lower troposphere are smaller than those evaluated from the Lacis and Hansen parameterization. But part of this difference is attributable to absorption bands which have been neglected by Chou and Arking. As previously discussed, these are the 0.72 and 6.3 μm bands together with most of the 0.81 μm band. We have employed the Goody model to test the importance of that portion of the 0.81 μm band which Chou and Arking did include, and we find that for all practical purposes they neglected the entire band.

In Fig. 6 we employ the Goody model to illustrate the impact of deleting the 0.72 and 0.81 μm bands, and then additionally the 6.3 μm band. Collectively these bands contributed as much as 0.2 K day^{-1} to the tropospheric heating rate, and this accounts for about half of the difference between Chou–Arking and Lacis–Hansen within the lower troposphere.

Also shown in Fig. 4 are heating rates determined from the absorptance parameterization of Wang (1976, his eq. 17), and these differ substantially from the other results. As have we, Wang

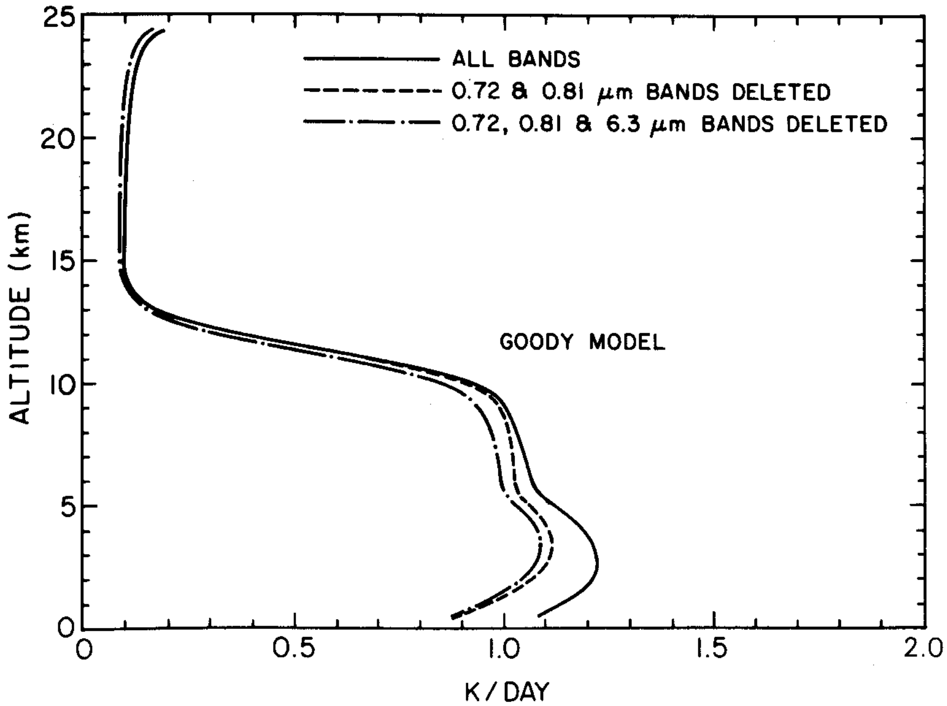

Fig. 6. A comparison of atmospheric heating rates for the same water vapor mass mixing ratio as in Fig. 4, showing the relative importance of the 0.72, 0.81 and 6.3 μm water vapor bands.

employed the Goody random band model together with Curtis–Godson scaling. For the 0.94 and 1.4 μm bands he employed line parameter data from the compilation of McClatchey et al. (1973), while for the 0.72 and 0.81 μm bands he used a fit of the Goody model to the measurements of Fowle (1915). For the 1.38 μm and longer wavelength bands he employed, for use within eq. (1), σ/δ from Ludwig et al. (1973), and α/δ from Ferriso et al. (1966). But the α/δ results of Ferriso et al. are band-averaged values which were determined from laboratory data for the 2.7/3.4 and 6.3 μm bands, and for which the data scatter was rather substantial (exceeding an order of magnitude). Thus it is possible that the differences shown in Fig. 4 are attributable to the α/δ values employed by Wang.

To be more specific on this point, we have replaced α/δ within our version of the Goody model by α/δ as used by Wang for $\omega \leqslant 8300$ cm^{-1}. which is the wavenumber range for which he employed the Ferriso et al. results. The comparisons shown in Fig. 7 indicate that this is indeed a major source of the discrepancy.

A further point pertains to single-parameter scaling which, for example, is discussed by Wang (1976) and by Chou and Arking (1981). From the perspective of an asymptotic limit, single-parameter scaling is exact in the strong-line limit (and of course in the weak-line limit), as is evident from eq. (5), and since the line half-width is a linear function of pressure, then eq. (7), as employed by Lacis and Hansen, corresponds to strong-line scaling under the assumption that the line half-width is inversely proportional to the square-root of temperature.

In Fig. 8 we compare heating rates as determined from the Goody random band model, both in its complete form (eq. 1) and in the strong-line limit (eq. 5). This shows that strong-line scaling can overestimate heating rates by as much as 0.15 K day^{-1}, and this was the motivation for our presenting eq. (8) which utilizes two-parameter scaling.

This further illustrates that when comparing different models, one is dealing with potential differences due *both* to different radiation formulations as well as different scaling approximations. Thus a true comparison of the Goody model and the Lacis–Hansen parameterization would be in the strong-line limit, and this is also illustrated in Fig. 8. For the troposphere the agreement is within 0.1 K day^{-1}, and again recall that stratospheric

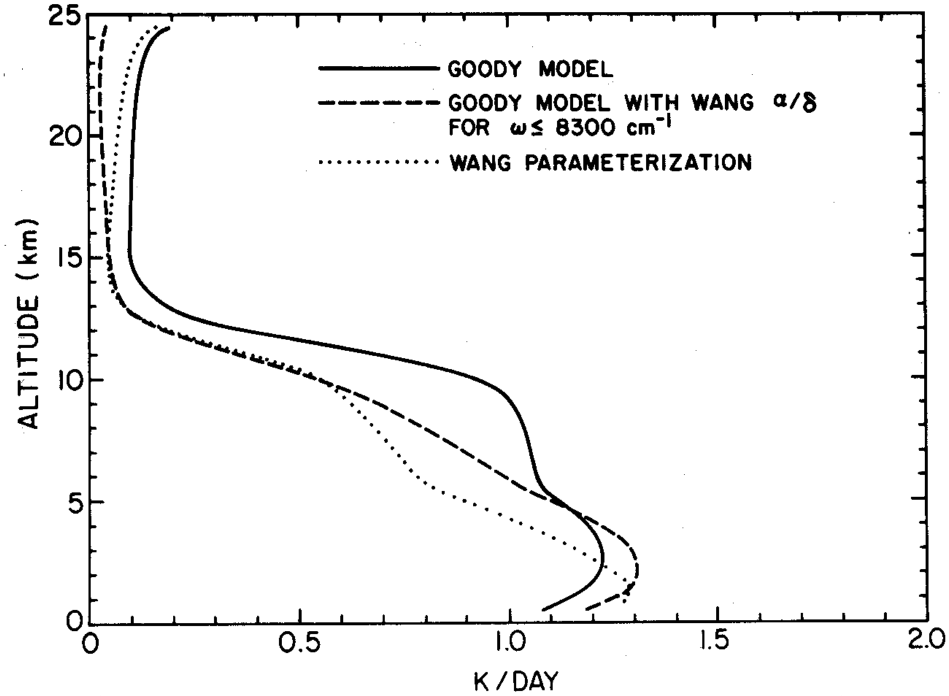

Fig. 7. A comparison of atmospheric heating rates for the same water vapor mass mixing ratio as in Fig. 4.

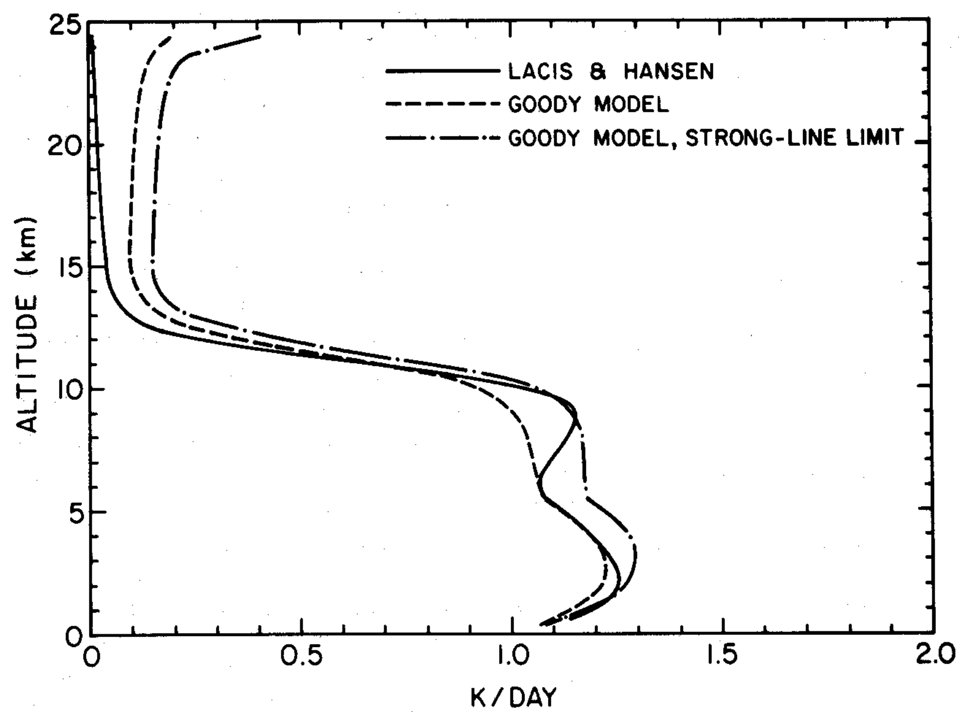

Fig. 8. A comparison of atmospheric heating rates for the same water vapor mass mixing ratio as in Fig. 4.

conditions lie outside the intended range of applicability of the Lacis–Hansen parameterization. When compared to the complete Goody model, differences increase to 0.15 K day^{-1} as a consequence of the use of strong-line scaling inherent in the Lacis–Hansen parameterization.

As a final point we note that Fouquart and Bonnel (1980), and Slingo and Schrecker (1982), both employing Lowtran 3B, compute heating rates which exceed within the upper troposphere and stratosphere those due to the Lacis–Hansen parameterization, a conclusion consistent with our comparisons. But as previously emphasized, such differences are modified when diurnal averaging is taken into account. Within the lower troposphere their heating rates are nearly 0.2 K day^{-1} less than those computed from the Lacis–Hansen parameterization, and the reason for this is not apparent, since Lowtran 3B includes the 0.72 and 0.81 μm bands, and it incorporates a single-parameter scaling which is very similar to the Lacis–Hansen parameterization.

5. Concluding remarks

The primary point of this paper is that, by employing a random band model as a diagnostic tool, it is possible to understand certain of the discrepancies which exist within the literature concerning atmospheric heating rates due to solar absorption by atmospheric water vapor. In particular we reaffirm McDonald's (1960) conclusion as to the importance of the 0.72 and 0.81 m water vapor absorption bands. We also illustrate that within the troposphere the Goody random band model and the Lacis–Hansen parameterization produce heating rates which are in quite reasonable agreement. Within the stratosphere the Lacis–Hansen parameterization yields heating rates that are smaller than those determined from the Goody model, a result which is not particularly surprising, since stratospheric water vapor amounts are below the stated range of applicability of the Lacis–Hansen parameterization. But care must be exercised in making such comparisons, and when diurnal averaging is taken into account for the stratosphere, the differences are less than 0.1 K day^{-1}.

6. Acknowledgements

We benefited from numerous discussions with Dr. V. Ramanathan. This work was supported by the National Science Foundation through Grant No. ATM 8212791.

REFERENCES

Chou, M.-D. and Arking, A. 1981. An efficient method for computing the absorption of solar radiation by water vapor. *J. Atmos. Sci. 38*, 798–807.

Ferriso, C. C., Ludwig, C. B. and Thomson, A. L. 1966. Empirically determined infrared absorption coefficients of H_2O from 300 to 3000K. *J. Quart. Spectrosc. Radiat. Transfer 6*, 241–275.

Fouquart, Y. and Bonnel, B. 1980. Computations of solar heating of the earth's atmosphere: A new parameterization. *Contr. Atmos. Phys. 53*, 35–62.

Fowle, F. E. 1915. The transparency of aqueous vapor. *Astrophys. J. 42*, 394–411.

Godson, W. L. 1955. The computation of infrared transmission by atmospheric water vapor. *J. Meteorol. 12*, 272–284.

Goody, R. M. 1952. A statistical model for water vapor absorption. *Q. J. R. Meteorol. Soc. 78*, 165–169.

Goody, R. M. 1964. *Atmospheric radiation.* London: Oxford University Press, 436 pp.

Harries, J. E. 1976. The distribution of water vapor in the stratosphere. *Rev. Geophys. Space Phys. 14*, 565–575.

Howard, J. N., Burch, D. E. and Williams, D. 1956. Infrared transmission of synthetic atmospheres, Parts I–V. *J. Opt. Soc. Amer. 46*, 186–190, 237–241, 242–245, 334–338, 452–455.

Kiehl, J. T. and Ramanathan, V. 1982. CO_2 radiative parameterization used in climate models: comparison with narrow band models and with laboratory data. *J. Geophys. Res. 88*, 5191–5207.

Lacis, A. A. and Hansen, J. E. 1974. A parameterization for the absorption of solar radiation in the Earth's atmosphere. *J. Atmos. Sci. 31*, 118–133.

Ludwig, C. B., Malkmus, W., Reardon, J. E. and Thomson, A. L. 1973. *Handbook of infrared radiation from combustion gases.* NASA SP-3080. 486 pp.

Malkmus, W. 1967. Random Lorentz band model with exponential tailed S^{-1} line-intensity distribution function. *J. Opt. Soc. Amer. 57*, 323–329.

McClatchey, R. A., Benedict, W. S., Clough, S. A., Buich, D. E., Calfee, R. F., Fox, K., Rothman, L. S. and Garing, J. S. 1973. AFCRL atmospheric absorption line parameters compilation, AFCRL Environmental Research papers No. 434. 78 pp.

McClatchey, R. A., Fenn, R. W., Selby, J. E., Volz, F. E., and Garing, J. S. 1972. Optical properties of the atmosphere 3rd ed., AFCRL Environmental Research Papers Number 411. 108 pp.

McDonald, J. E. 1960. Direct absorption of solar radiation by atmospheric water vapor. *J. Meteorol. 17*, 319–328.

Rodgers, C. D. 1968. Some extensions and applications of the new random model for molecular band transmission. *Q. J. Meteorol. Soc. 94*, 99102.

Rodgers, C. D. and Walshaw, C. D. 1966. The computation of infrared cooling rate in planetary atmospheres. *Q. J. R. Meteorol. Soc. 92*, 67–92.

Rothman, L. S. 1981. AFGL atmospheric absorption line parameters compilation: 1980 version, *Appl. Opt. 20*, 791–795.

Slingo, A. and Schrecker, H. M. 1982. On the shortwave radiative properties of stratiform water clouds. *Q. J. R. Meteorol. Soc. 108*, 407–426.

Thekaekara, M. P. 1972. Solar energy outside the earth's atmosphere. *Solar energy 14*, 109–127.

Wallace, L., Prather, M. and Belton, M. J. S. 1974. The thermal structure of the atmsophere of Jupiter. *Astrophys. J. 193*, 481–493.

Wang, W.-C. 1976. A parameterization for the absorption of solar radiation by water vapor in the Earth's atmosphere. *J. Appl. Meteorol. 15*, 21–27.

Yamamoto, G. 1962. Direct absorption of solar radiation by atmospheric water vapor. carbon dioxide and molecular oxygen. *J. Atmos. Sci. 19*, 182–188.